Enthalpy Flux in Extreme Winds
and the Roles of Sensible, Latent and Spray Heat Transfer Processes

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LONG-TERM GOALS

- To determine the coefficients for sensible and latent heat transfer (Stanton and Dalton numbers) in high and extreme winds.
- To understand, quantify and parameterize the role of spray in these fluxes.

OBJECTIVES

- To conduct laboratory tests of the cooling of a heated water body under unstable and stable conditions, with neutral conditions deduced from the asymptotic matching of unstable and stable conditions.
- To separate the sensible and latent parts of the enthalpy flux by repeating calorimetric experiments at different Bowen ratios.
- To observe and measure the spray production in both fresh and salt-water and to relate the production rate to the wind speed, the intensity of wave breaking and the entrainment of bubbles.

APPROACH

This project has been undertaken in the wind-wave facility at the Rosenstiel School of Marine and Atmospheric Science, University of Miami. ("Air-Sea Interaction Saltwater Tank - ASIST"). ASIST (http://www.rsmas.miami.edu/groups/asist/) has a working section of 1 m x 1 m x 15 m. The water depth can be selected up to 0.5 m and at this maximum depth the (centerline) wind speed can be selected between 0 and 30 m/s (equivalent to greater than 100 knots at 10 m height). At this maximum speed wave breaking is intense and the tops of the wave crests are blown into spume. The calorimetric use of the tank over the full range of wind speeds provides accurate estimates of the surface heat transfer. The approach is to heat or cool the water (using built in heat exchangers) by 2 to 5° C above/below the air temperature and observe the cooling/heating rate of the water body with 4 precision thermistors placed upstream and downstream in both air and water. The room temperature (hence wall temperature) is maintained close to the temperature of the water to minimize the radiative

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transfer. Remaining radiative transfers are estimated by observing the heating/cooling of the water without any air flow, and with the water surface covered with an insulating sheet.

The water is continuously pumped at a slow speed (0.08 m/s) to assure that the water column is well mixed. However, in calculating the heat and vapor fluxes across the air-sea interface it is necessary to account for the difference between the surface skin temperature and the bulk temperature. To directly observe the skin temperature and compare it to bulk measurements a FLIR infrared radiometer imaged the water surface during the experiments. There was no mean bias between the enthalpy transfer coefficient calculated using the subsurface bulk temperature and the radiometer observed skin temperature, demonstrating that the water column was well mixed.

The (“Black Stack”) thermistor system provided accuracy and precision of ± 0.002° C and this enables a 2% estimate of the heat loss/gain in 5 minutes to 30 minutes depending on the wind speed. To prevent direct impingement of spray on the probe, the downstream thermistor was placed in a sheltered port through which the tank air was pumped. Before spray formed there was no mean difference in the observed temperature in the port compared with a probe placed directly in the flow, demonstrating that the system was effective at extracting and correctly measuring the temperature of the tank air. Figure 1 shows an example of the measured temperature and wind speed during a run. Polynomial fits to the temperature allow a continuous estimate of the total heat loss. The specific humidity was measured with Li-Cor infra-red absorption devices at both the upstream and downstream ends of the wind tunnel.

This facility was acquired through DURIP grant number N00014-98-1-0261. A recent DURIP grant (number ONR N000140510852) has provided upgrades to its instrumentation systems that will be exploited as this project continues. In particular, a newly acquired particle generation system for the air-flow in ASIST will enable the mapping of the velocities above the surface. In combination with a newly acquired 3-D traverse, full volume mapping of the air flow above breaking waves will be possible.

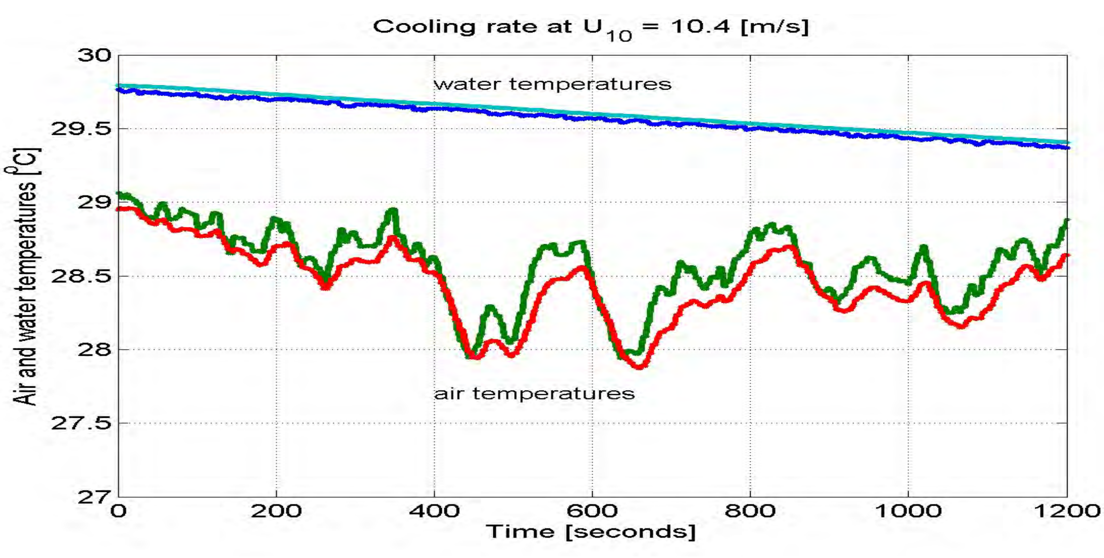

Figure 1. An example of the method of measurement of heat exchange. The upper water temperature curve is the input (upstream) water temperature, while the lower air temperature curve is the input (upstream) air temperature.

WORK COMPLETED

We have successfully executed a series of laboratory experiments in ASIST that included calorimetric measurements of the total (moist) enthalpy exchange coefficient (C_K) at many combinations of wind speeds (U_{10} ranging from 4-42 m/s), air-sea temperature differences and ambient humidity. This work was presented at the fall 2006 AGU meeting and is the basis for a paper in preparation for the journal Nature:Geosciences. Further analysis of this expanded set of measurements is ongoing and will included in the Masters thesis of Dahai Jeong.

RESULTS

The observed enthalpy flux coefficient C_K varied between 0.00085 and 0.0015 for U_{10N} ranging from 0.4-38 ms^{-1} (Figure 2). Direct flux measurements of C_k made as a part of the CBLAST program varied over a larger range from 0.0004 to 0.0028 over U_{10N} from 17 to 29 ms^{-1}. In the lightest winds (before waves form) the ASIST C_K decreased with increasing wind as is characteristic of aerodynamically smooth flow (Ocampo-Torres et al., 1994). Once waves began to form and the boundary roughened the rate of decrease of C_K slowed to a minimum ($\frac{\partial C_K}{\partial U_{10N}} = 0$) at 2.5 ms^{-1}. Further increasing the wind speed led to increasing aerodynamic roughness and an increasing fraction of the surface being ventilated by wave breaking. This was reflected in an increase in the ASIST C_K from 2.5 ms^{-1} to 18 ms^{-1}, which agreed well with the COARE (Fairall et al., 2003), HEXOS (Decosmo et al., 1996) and CBLAST observations over this range. There was distinctly lower scatter in the laboratory observations than in the field due to the high precision of the calorimetric technique and the temperature sensors that were used to observe C_K. In fact the 95% confidence intervals on both the HEXOS and CBLAST C_K encompass the more accurate ASIST measurements. This provides further cross-verification of field and laboratory enthalpy flux measurements. Beyond the range where high wind field observations were available (U_{10N} > 29 ms^{-1}), the ASIST estimates of C_K decreased slightly and saturated at a level of 0.0012. Once the surface was roughened, up to the maximum winds observed, the enthalpy exchange coefficient was invariant with U_{10N}.

The ASIST C_K/C_D matched the revised COARE relationship and the CBLAST values at the lowest winds, but were significantly (at 95 % confidence level) higher than both COARE and HEXOS from 2 to 18 ms^{-1} (Figure 3). Given the close agreement for C_K (Figure 2) it is clear that this difference can be attributed entirely to differences in the drag coefficient (C_D), which was lower in ASIST than in the field. This was expected because laboratory observations of C_D have previously shown lower values than field observations in low to moderate winds (Donelan et al., 2004), likely due to the significantly smaller fetch values of the wave field in a laboratory relative to the real ocean surface.

The ASIST C_K/C_D (Figure 3) decreased throughout the wind range from 18 ms^{-1} to 29 ms^{-1} as C_K remained relatively constant and C_D increased with wind speed. They were somewhat higher than the CBLAST values over the lower part of this wind range, but agreed to within 95% confidence for winds greater than 23 ms^{-1}. At $U_{10N} \approx 25$ ms^{-1} C_K/C_D decreased below 0.75 which had been suggested as a lower limit on the value in the high wind region of hurricanes (Emanuel, 1995) The C_K/C_D values were invariant at a level of ~0.5 for winds greater than 30 ms^{-1} up to the maximum observed winds of nearly 40 ms^{-1}. These results suggest that the maximum potential intensity limit cannot apply in intense hurricanes as observed by Montgomery et al. (2006) in Hurricane Isabel.

IMPACT/APPLICATIONS

The theoretical analyses of Emanuel (1995) concludes that the maximum potential intensity (MPI) of hurricanes depends on the relative magnitudes of the enthalpy flux and the momentum flux and that the current (pre 2003) parameterizations of the bulk drag and enthalpy coefficients would preclude the existence of category 4 and stronger hurricanes. Through this effort we have been able to provide the first direct measurements of the transfer coefficients in hurricane force winds. This research builds upon a successful set of laboratory observations of the bulk transfer coefficients for momentum (Donelan et al., 2004) in ASIST as well as field observations made through the ONR supported CBLAST program (Black et al., 2007; French et al. 2007). We have shown that the expectation of increasing roughness with increasing wind speed, such as described by the generally used bulk drag transfer coefficients (e.g. Large and Pond, 1981), finds a limit at wind speeds of tropical storms and hurricanes. Dropsonde derived estimates of the drag coefficient in hurricanes by Powell et al. (2003) also demonstrated a limiting value. The observed structure of the wind driven ocean current beneath hurricanes reflects this "saturation" of the drag coefficient in high winds (Zedler et al., 2002, Jacob and Shay, 2003; Sandford et al., 2007). The enthalpy coefficient has been shown through this set of experiments to be essentially constant up to a wind speed of 40 ms^{-1} (Haus et al., 2007).

Our results contradict the theoretical arguments by Barenblatt et al. (2005) that there will be an immediate and sudden reduction of drag and/or increase in enthalpy transfer upon the formation of spray. However, we cannot rule out that significant changes in C_K or C_K/C_D may occur in the eye wall of intense hurricanes as sea spray effects become more important. Systematic exploration of the generation of spray and its role in the enthalpy and momentum fluxes is required. The components of the enthalpy flux are: 1) the direct turbulent transfer of "sensible" heat by the vertical movement of relatively cool or warm parcels of air: 2) the direct turbulent transfer of latent heat by the differential vertical motion of more or less moist air; 3) the transport and phase changes of spray droplets released from the surface; 4) radiative transfer between various levels of the two fluids. As this research thrust continues, we plan to explore 1, 2 & 3 through additional laboratory experiments.

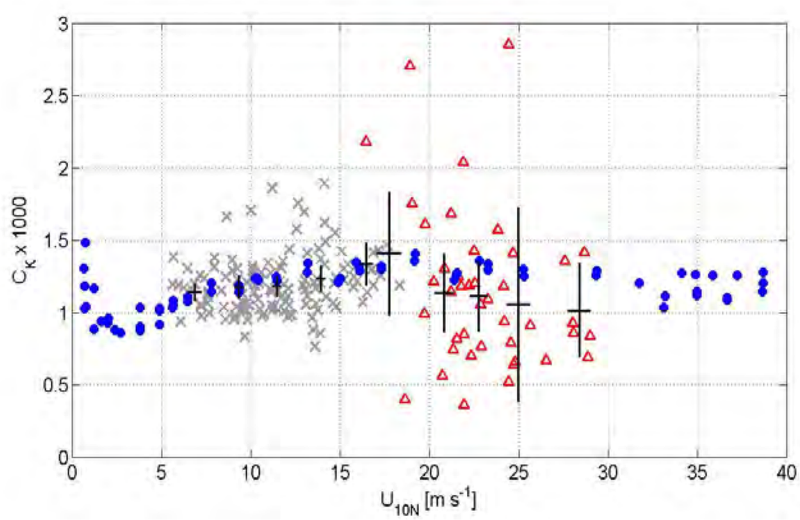

Figure 2. (Left) Wind speed dependence of total heat exchange coefficient. ASIST laboratory results (●) and CBLAST (△)measurements shown with HEXOS results (x). After binning observations by wind speed the mean and 95% confidence intervals of the combined HEXOS and CBLAST field data are shown in black.

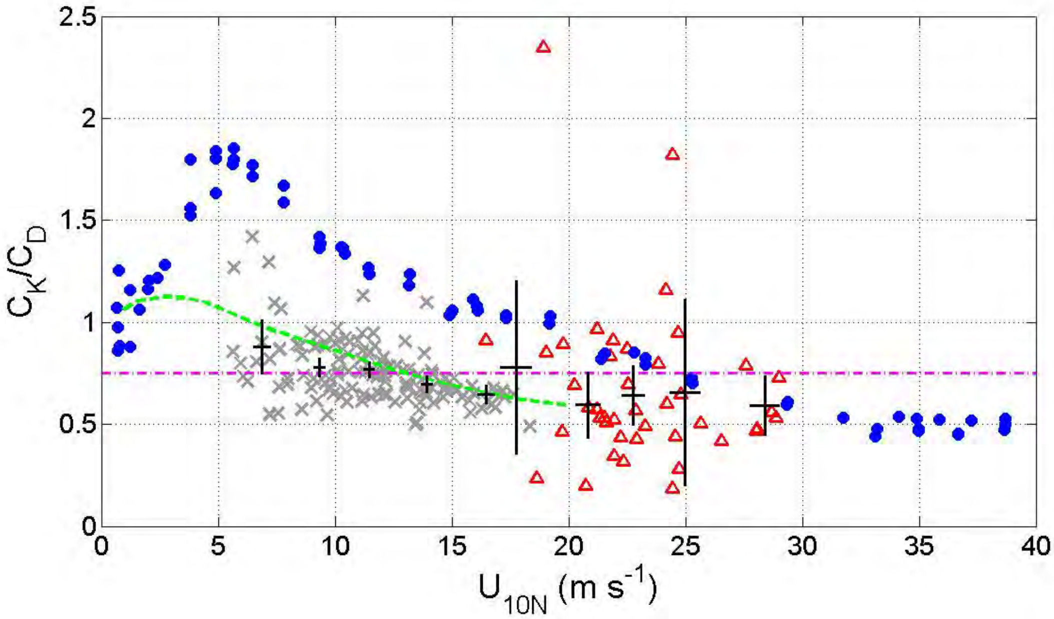

Figure 3. Wind speed dependence of CK/CD total heat exchange coefficient. ASIST laboratory results (●) and CBLAST (∆)measurements shown with HEXOS results (x). After binning observations by wind speed, the mean and 95% confidence intervals as determined from a t-distribution of the combined HEXOS and CBLAST field data are shown in black. Revised COARE15 relationship is shown (--), along with the threshold value of 0.75 suggested by Emanuel (1995).

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